Space Transportation Infrastructure Supported By Propellant Depots

Presentation for the Huntsville Alabama L5 Society

June 7, 2012

Based on an Advanced Concepts study and paper presented at the AIAA Space 2011 Conference and Exposition by David Smitherman and Gordon Woodcock, with additional analysis by the Advanced Concepts Office for possible SLS Integration

Abstract

A space transportation infrastructure is described that utilizes propellant depot servicing platforms to support all foreseeable missions in the Earth-Moon vicinity and deep space out to Mars. The infrastructure utilizes current expendable launch vehicle (ELV) systems such as the Delta IV Heavy, Atlas V, and Falcon 9, for all crew, cargo, and propellant launches to orbit. Propellant launches are made to a Low-Earth-Orbit (LEO) Depot and an Earth-Moon Lagrange Point 1 (L1) Depot to support new reusable in-space transportation vehicles. The LEO Depot supports missions to Geosynchronous Earth Orbit (GEO) for satellite servicing, and to L1 for L1 Depot missions. The L1 Depot supports Lunar, Earth-Sun L2 (ESL2), Asteroid, and Mars missions. New vehicle design concepts are presented that can be launched on current 5-meter diameter ELV systems. These new reusable vehicle concepts include a Crew Transfer Vehicle (CTV) for crew transportation between the LEO Depot, L1 Depot and missions beyond L1; a new reusable Lunar Lander for crew transportation between the L1 Depot and the lunar surface; and a new reusable Deep Space Habitat (DSH) with a CTV to support crew missions from the L1 Depot to ESL2, Asteroids, and a Mars Orbital Depot. The LEO Depot, L1 Depot, and Mars Orbital Depot are based on International Space Station (ISS) heritage hardware. Data provided includes the number of launches required for each mission utilizing current ELV systems (Delta IV Heavy or equivalent) and the approximate vehicle masses and propellant requirements. Also included is a discussion on affordability with ideas on technologies that could reduce the number of launches required and thoughts on how this infrastructure might be implemented incrementally over the next few decades. The potential benefits of this propellant depot infrastructure include competitive bidding for ELV flights and propellant services, development of new reusable in-space vehicles, and development of a multiuse infrastructure that can support many government and commercial missions simultaneously.

Space Infrastructure Overview

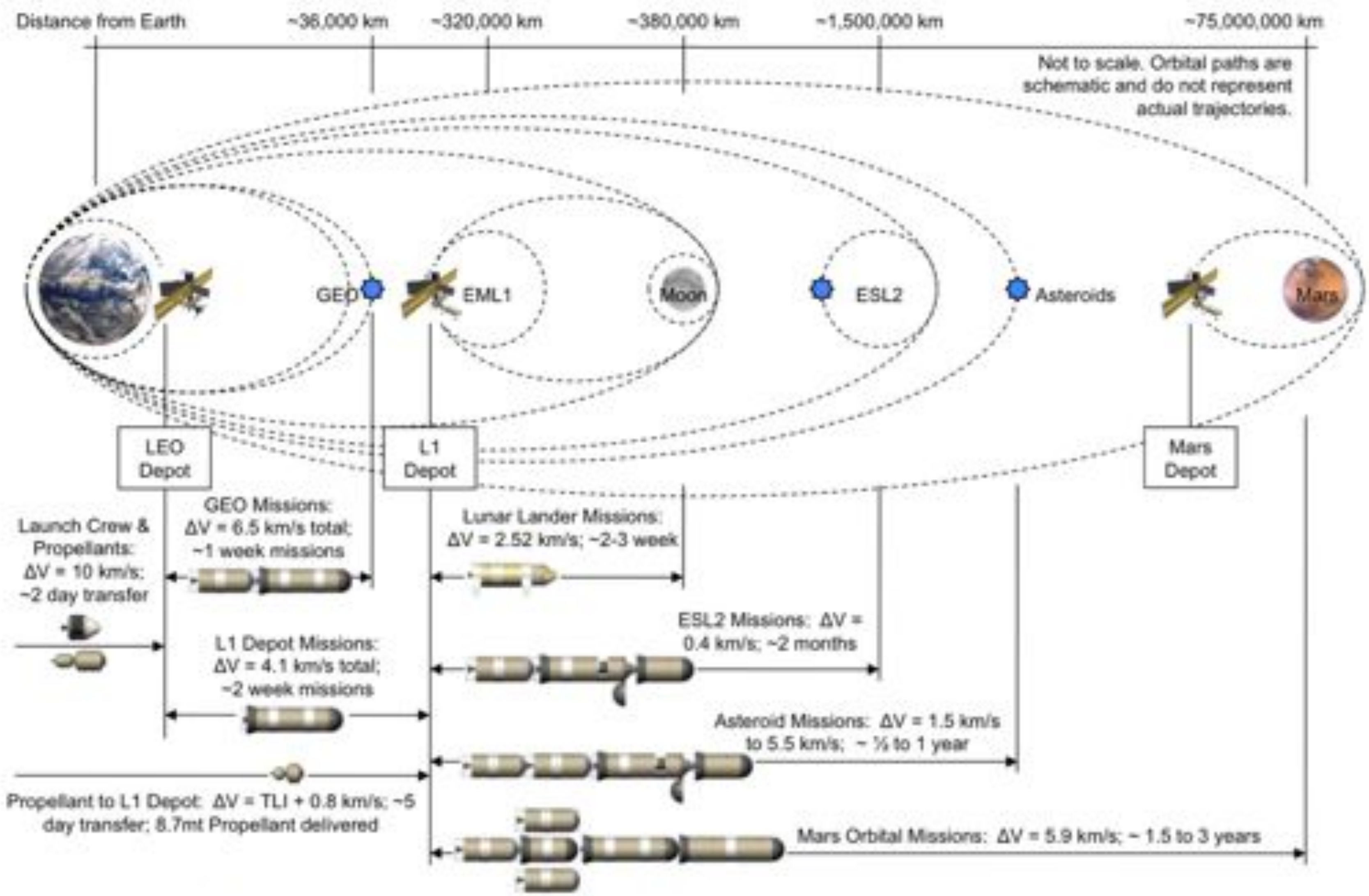


Figure 1. Space Infrastructure Overview. *Potential destinations are shown utilizing current ELV systems and a new reusable in-space transportation infrastructure supported by propellant depots.*

GEO Satellite Servicing

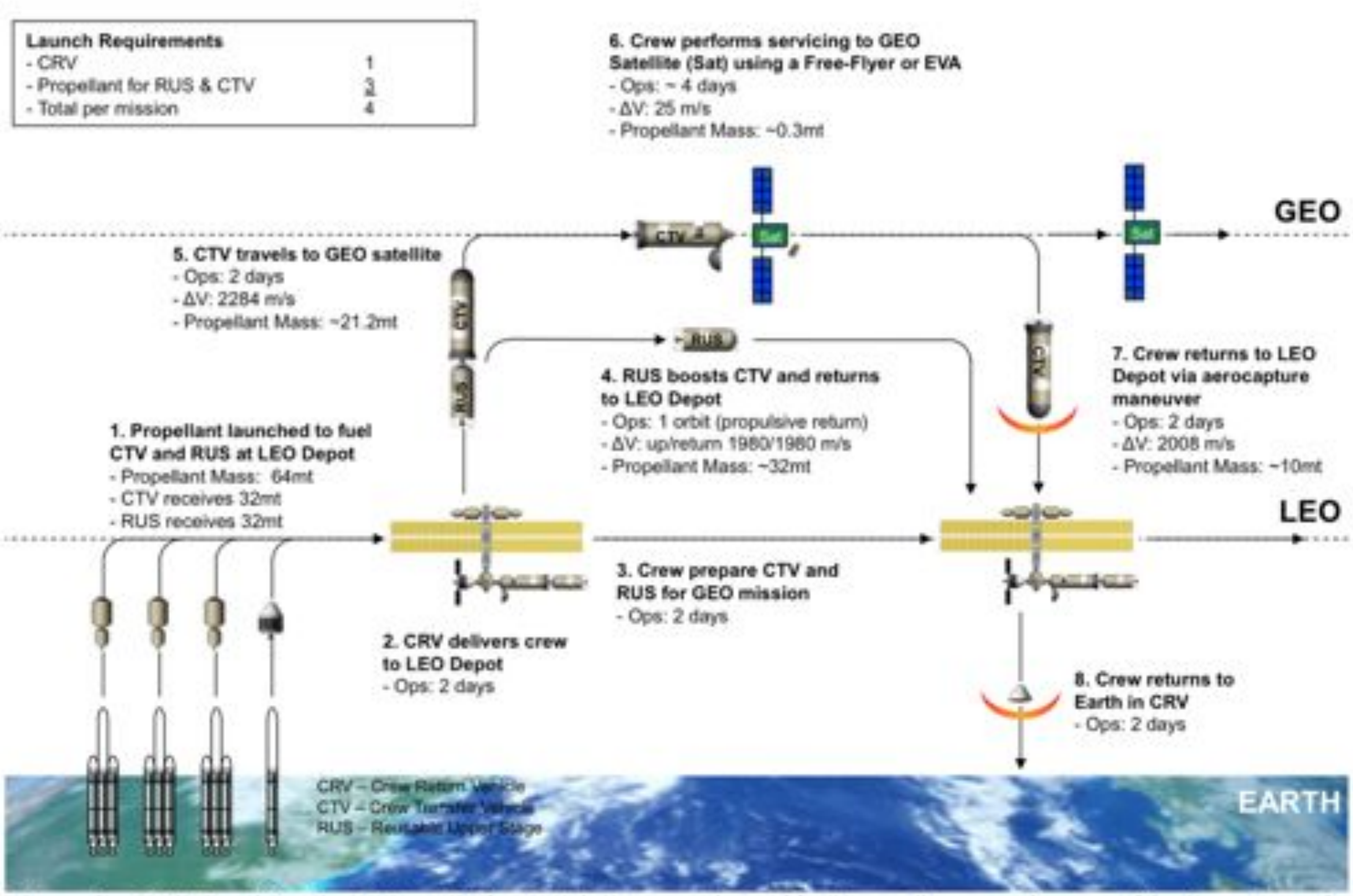


Figure 2. GEO Satellite Servicing. *With a LEO Depot, a Reusable Upper Stage, and a reusable Crew Transfer Vehicle, human satellite servicing missions can be done as needed with 3 propellant launches and 1 crew launch per mission. See Appendix A-1 for GEO Satellite Servicing Reference Profile details.*

Low Earth Orbit Depot

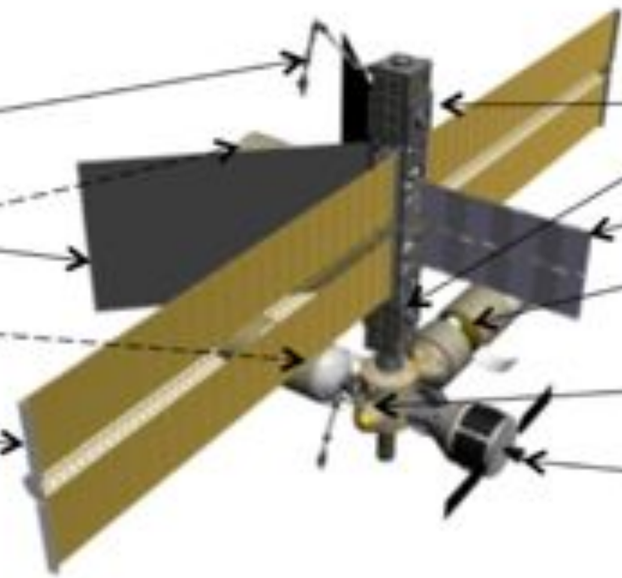


Figure 3. LEO Depot. *A LEO Depot is shown based on ISS heritage hardware consisting of a truss section with docking ports, solar arrays, radiators, sunshield protecting a propellant storage tank, and a pressurized node module. Attached vehicles include a Reusable Upper Stage, reusable Crew Transfer Vehicle, and a Crew Return Vehicle.*

Reusable Crew Transfer Vehicle

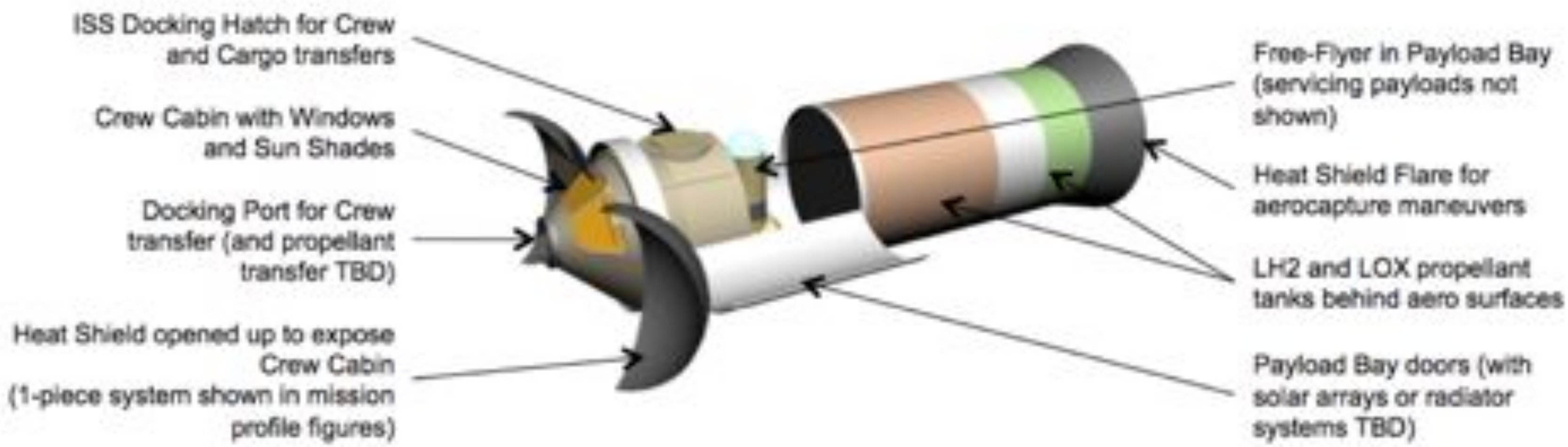


Figure 4. Crew Transfer Vehicle. *This configuration for the reusable Crew Transfer Vehicle shows a crew cabin and docking mechanism in the nose behind an open spherical heat shield, the remainder of the crew cabin behind payload bay doors, and an open bay for payloads that includes a human Free-Flyer servicing vehicle.*

Earth-Moon L1 Depot

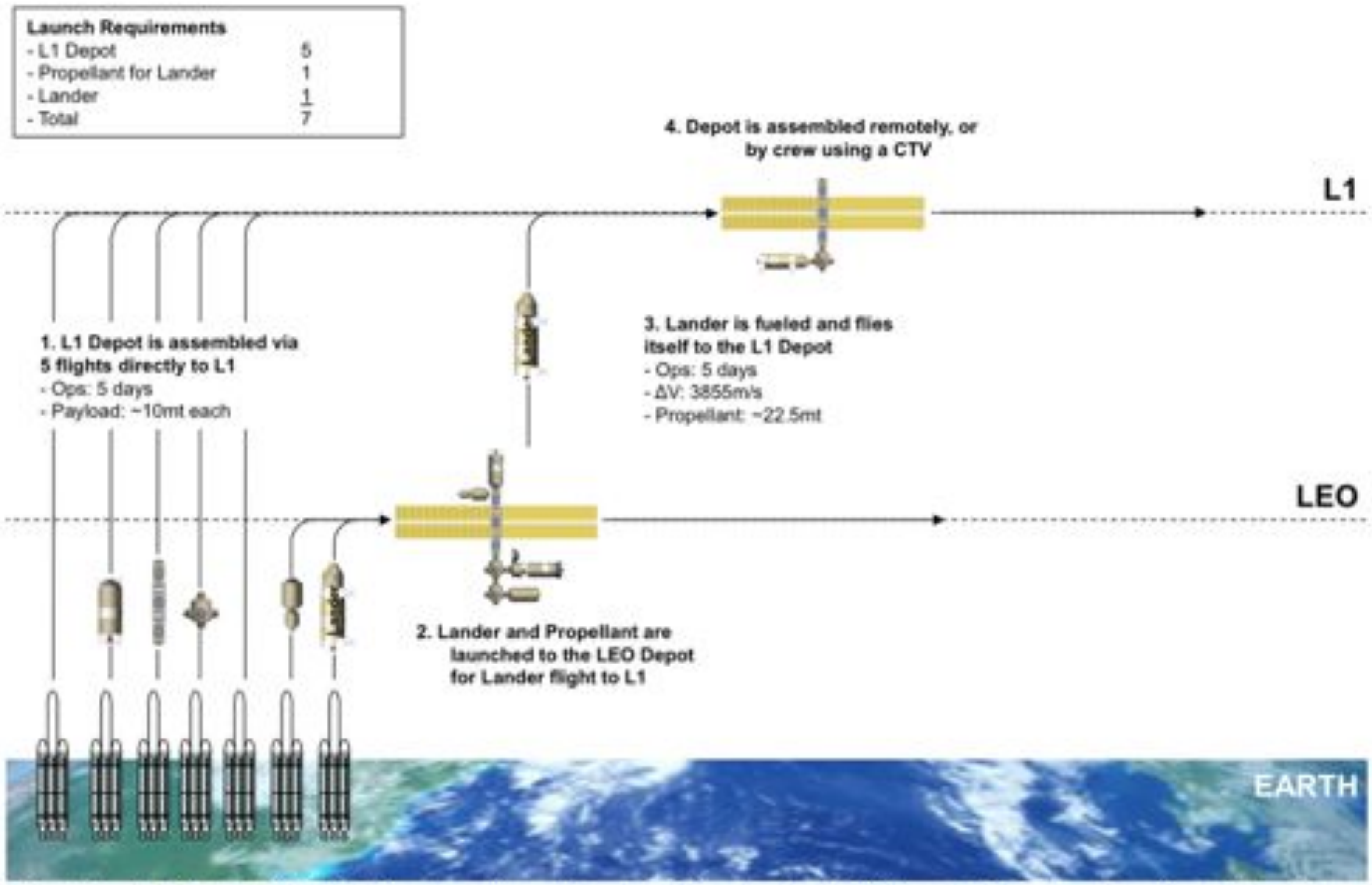


Figure 5. L1 Depot. *The L1 Depot configuration is similar to the LEO Depot. Five launches directly to L1 are required for depot hardware deliver, and two launches to the LEO Depot for the reusable Lander and its' propellant. The Lander once fueled can fly itself from the LEO Depot to the L1 Depot.*

Lunar Missions

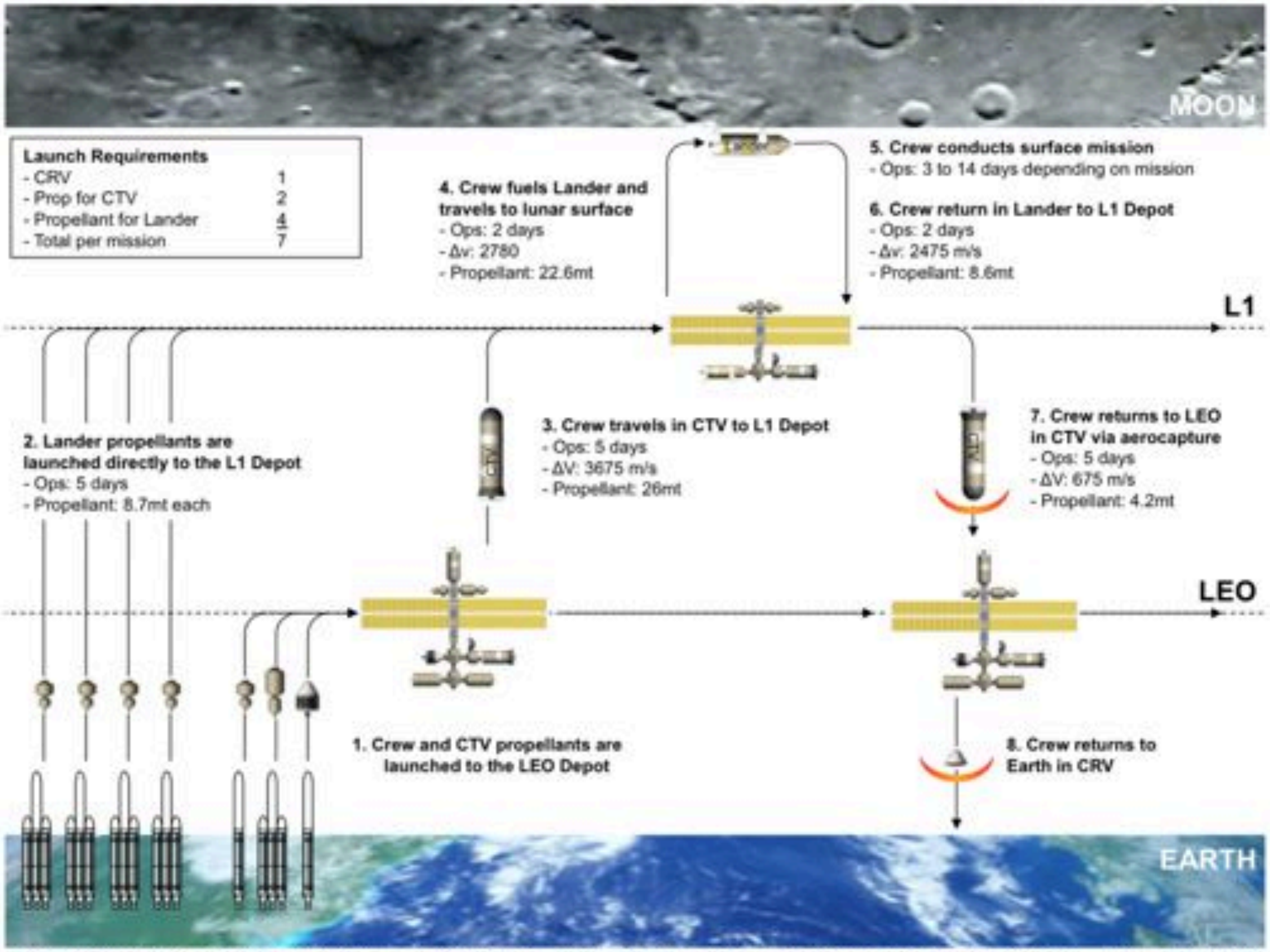
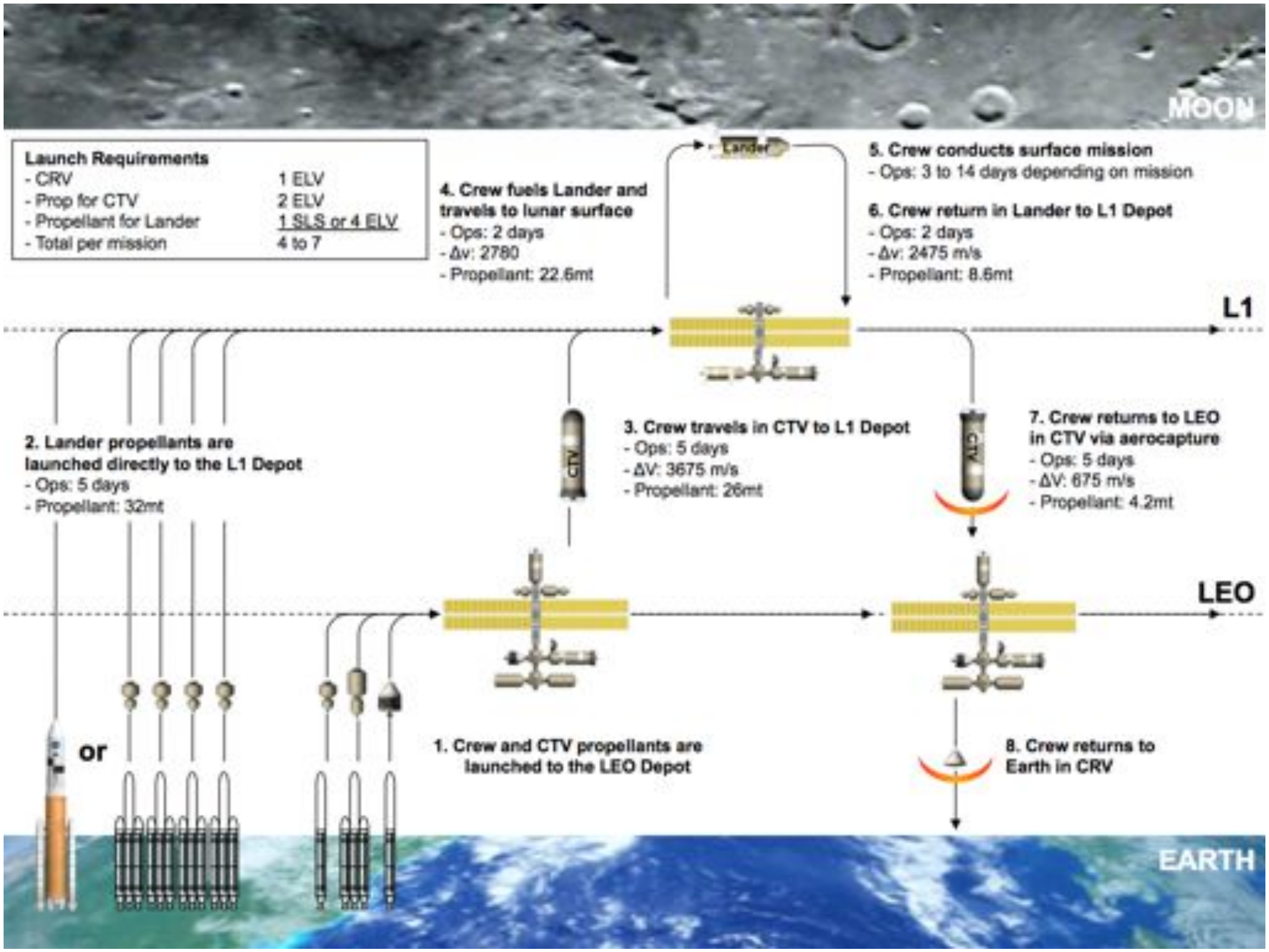


Figure 6. Lunar Missions. *With a LEO Depot, a L1 Depot, a reusable Crew Transfer Vehicle, and a reusable Lunar Lander, human missions can be done as needed to the surface of the Moon with 6 propellant launches and 1 crew launch per mission. See Appendix A-2 for the CTV and Appendix A-3 for the Lunar Lander Reference Profile details.*

Lunar Missions
With SLS Integration



SLS integration into this Lunar mission concept could include providing propellants to the L1 Depot in a single launch.

Reusable Lunar Landers

Figure 7. Lunar Lander. *This configuration for a reusable Lunar Lander shows a crew cabin at the forward end with four landing engines behind each of the four deployed landing legs. Two orbital transfer and descent engines are located at the aft end.*

Figure 8. Cargo Lander. *This configuration for a reusable Cargo Lander utilizes two standard crew Landers without the crew cabin at the forward end. The payload is suspended from a truss structure between the two vehicles.*

L1 Depot Expansion

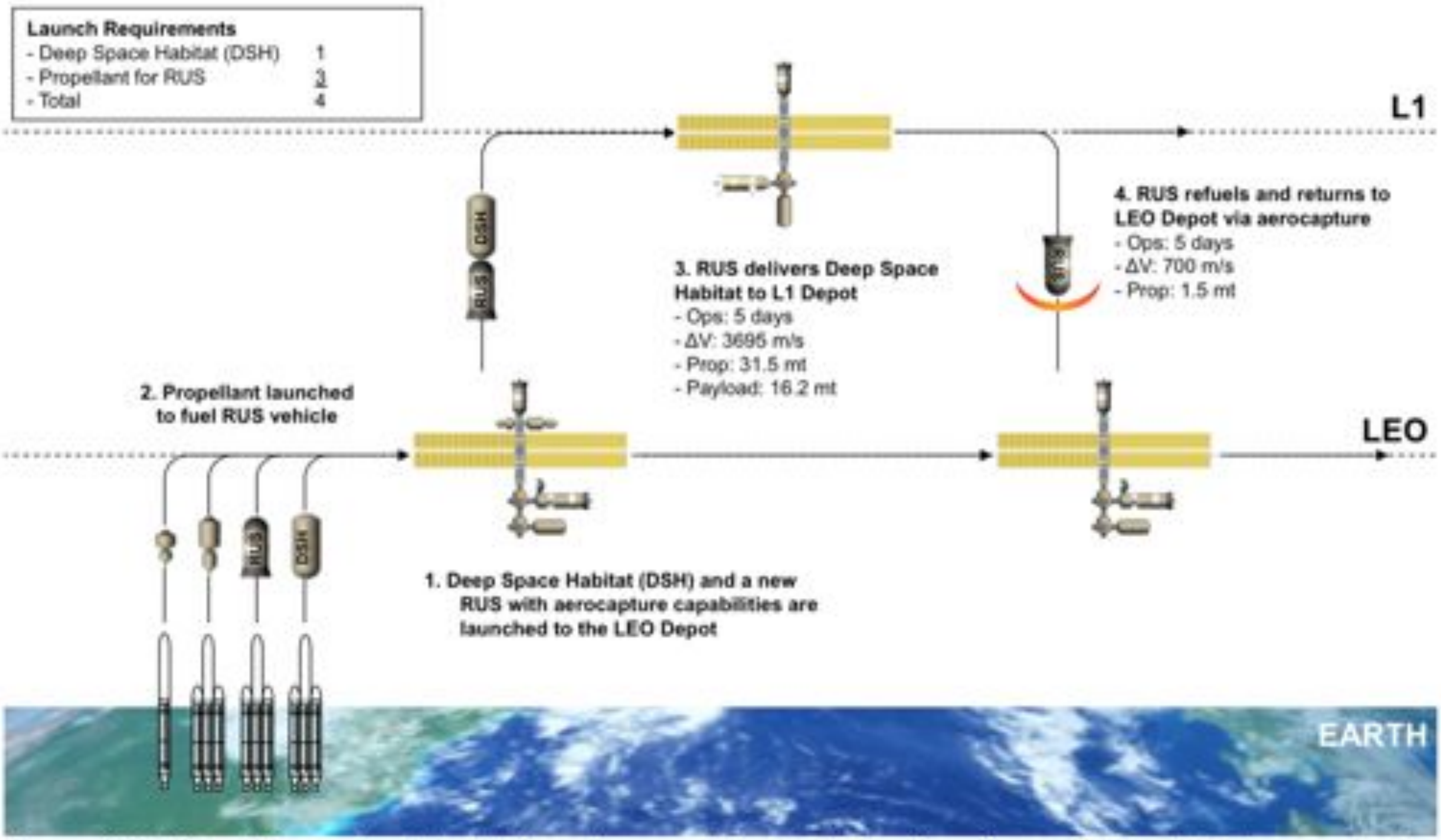


Figure 9. L1 Depot Expansion. *The L1 Depot is expanded to include a Deep Space Habitat(s) for human missions to ESL2, near Earth asteroids, and Mars missions. A reusable upper stage with aerocapture capabilities is also added for cargo deliveries to L1.*

Earth-Sun L2 Missions

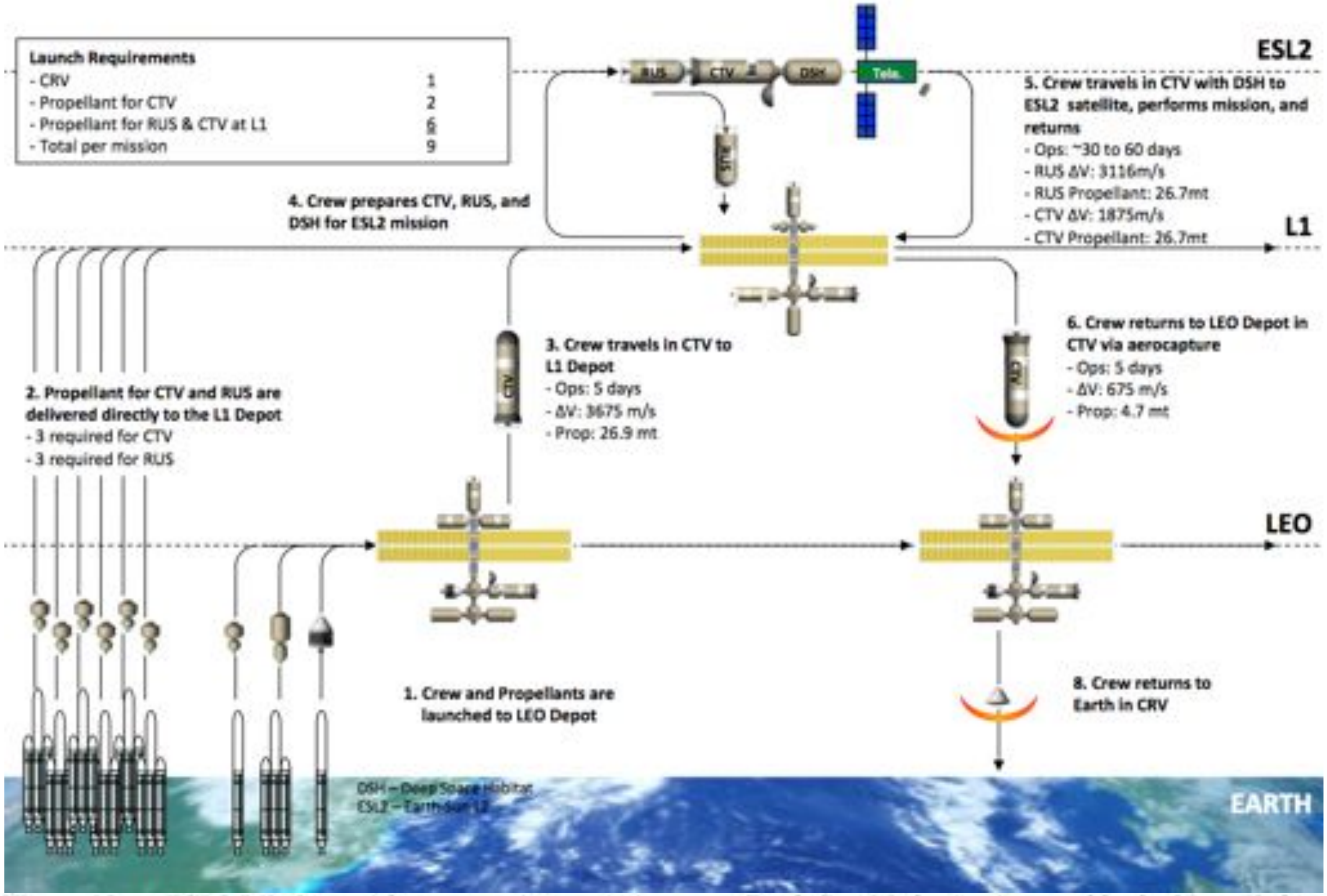


Figure 10. ESL2 Missions. *A human servicing mission to an Earth-Sun L2 destination would take 30 to 60 days and requires a RUS, CTV, and DSH operating out of the L1 Depot. One crew launch and eight propellant launches for a total of nine launches per mission would be required. See Appendix A-5 for ESL2 Mission Reference Profile details.*

Reusable Deep Space Habitat

Figure 11. Deep Space Habitat Cut-Away View. *This configuration for a Deep Space Habitat is about the size of the ISS Lab and Node modules combined. It includes ISS type racks, an internal airlock, and docking ports at each end and on the sides at the airlock location.*

Asteroid Missions

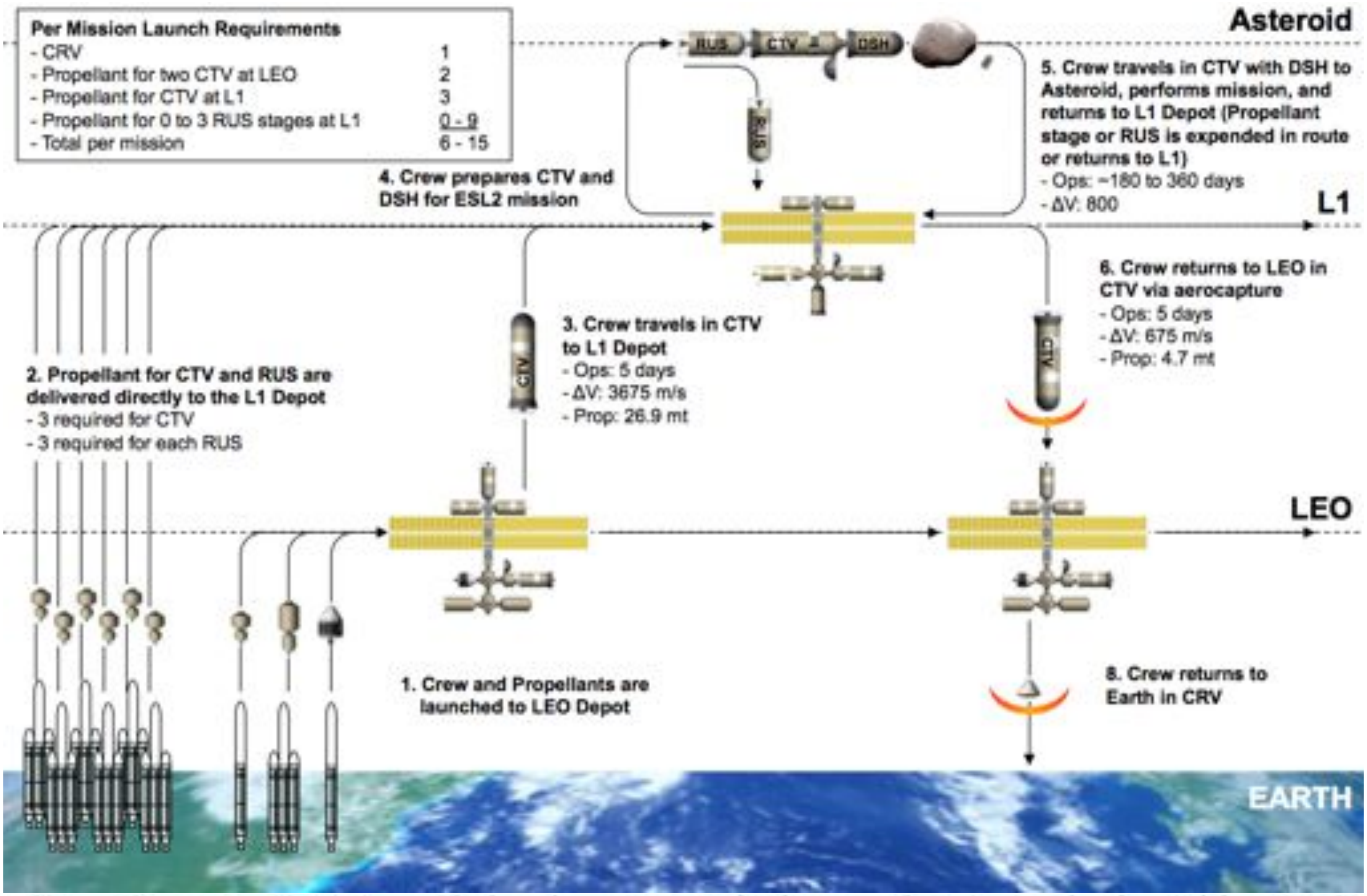


Figure 12. Asteroid Missions. *The launch requirements for the asteroid missions analyzed varied from 6 to 15 launches per mission including propellant and crew. In some scenarios all elements are reusable and in others only the CTV and DSH are reusable.*

Mars Orbital Depot Delivery

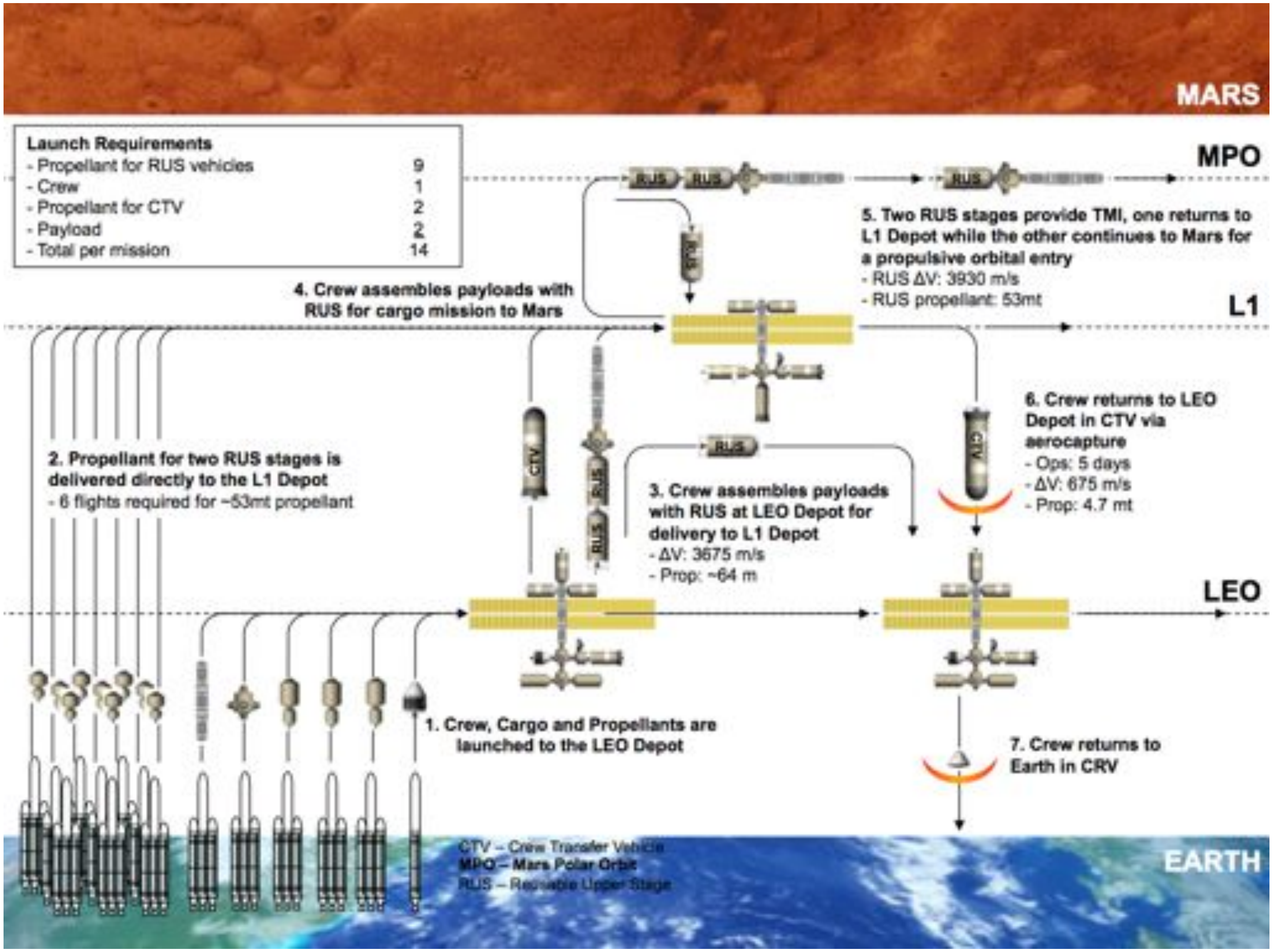


Figure 14. Mars Orbital Depot Delivery. *The Mars Orbital Depot would require about 14 launches to deliver ~40 mt to the L1 Depot for transfer to Mars orbit. Appendix A-6 provides a reference profile for delivery of the Mars Orbit Depot from the L1 Depot to Mars orbit.*

Mars Crew Missions

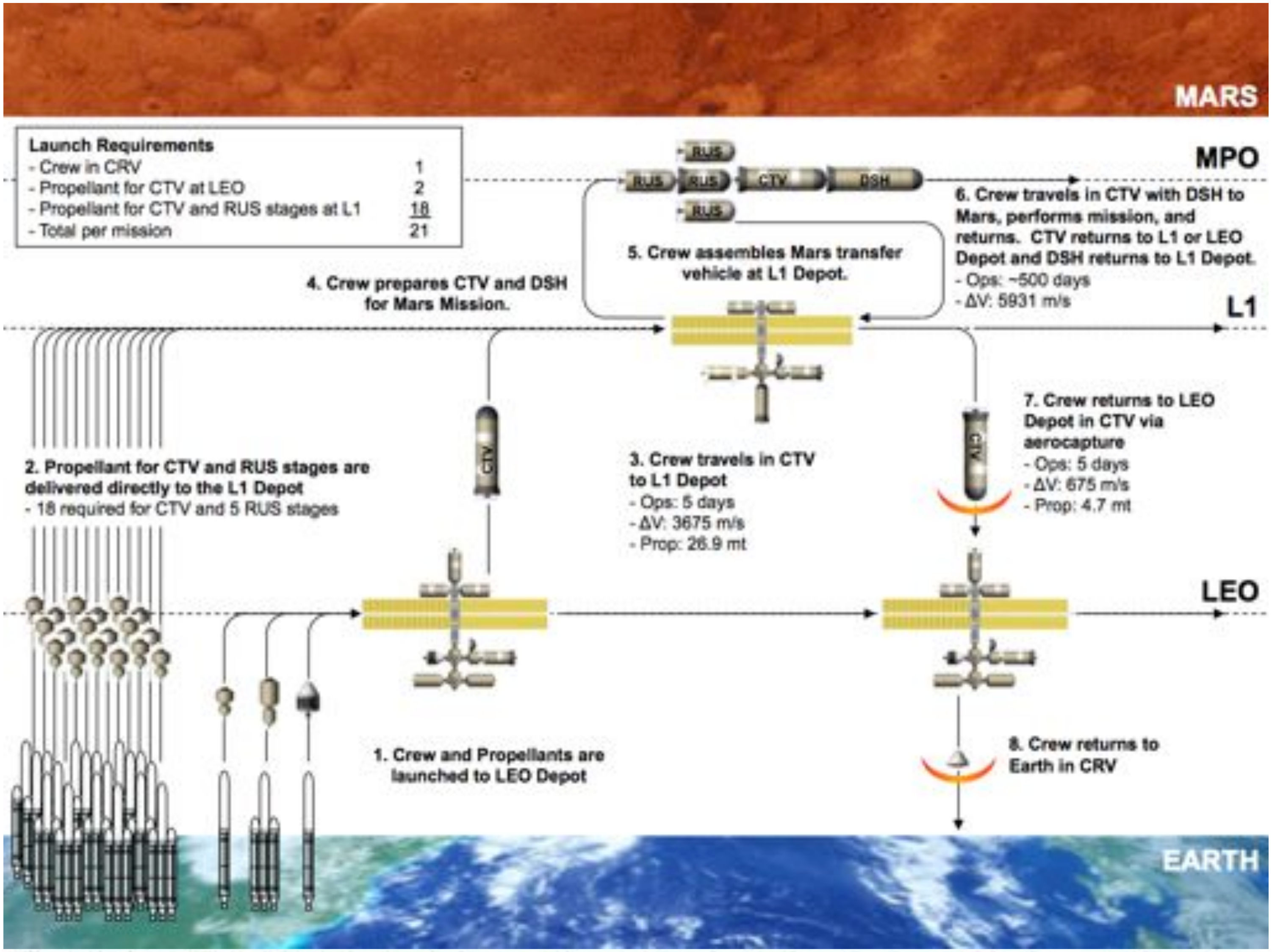
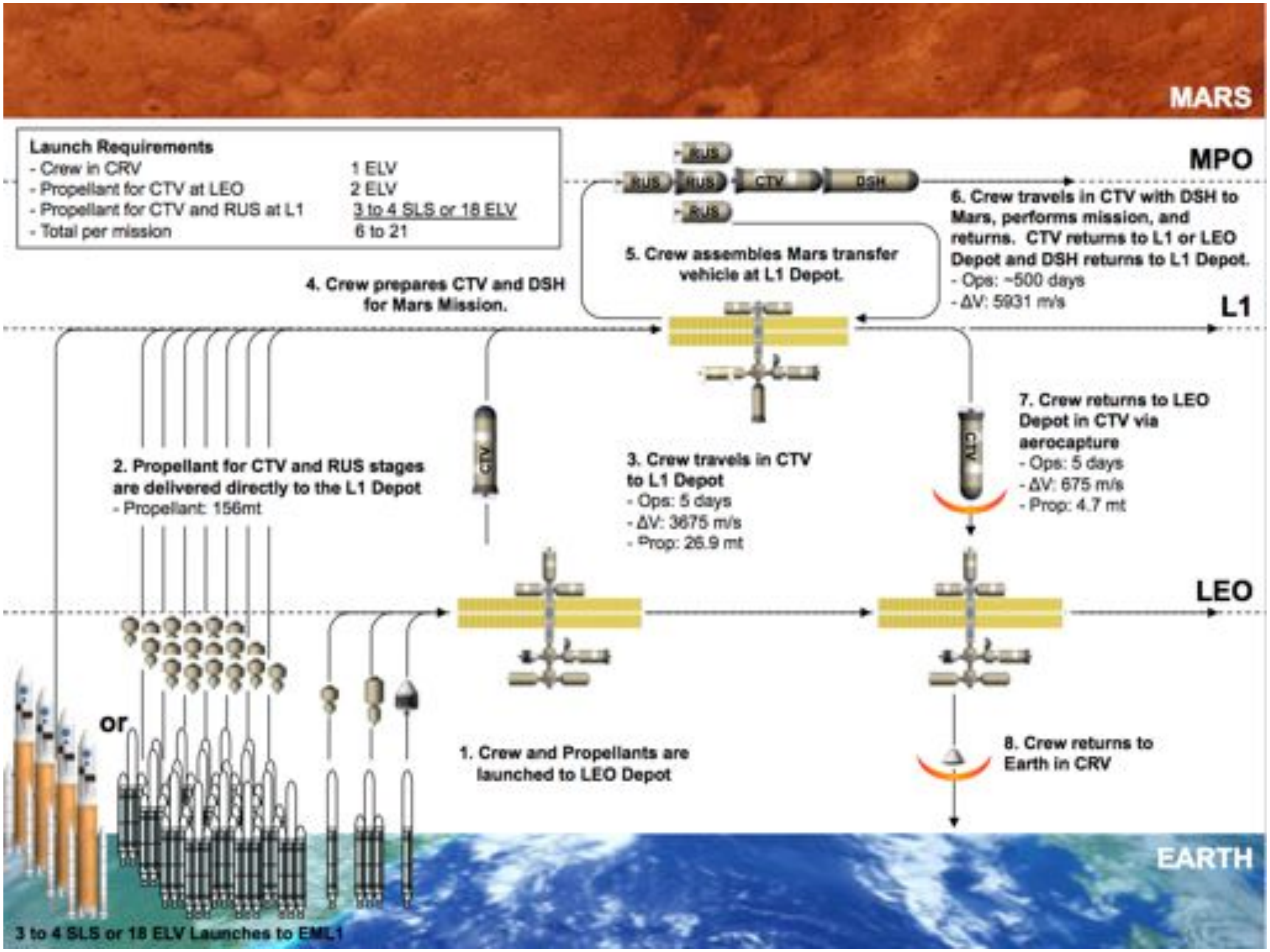


Figure 15. Mars Crew Missions. *A typical crew mission to Mars during the early phases of development will require a CTV, DSH, and 4 RUS vehicles. See Appendix A-7 for a typical Crew Mission Profile to Mars orbit.*

Mars Crew Missions
With SLS Integration



SLS integration into this Mars mission concept could include providing propellants to the L1 Depot in 3 or 4 launches.

Mars Orbital Depot Mission Concept

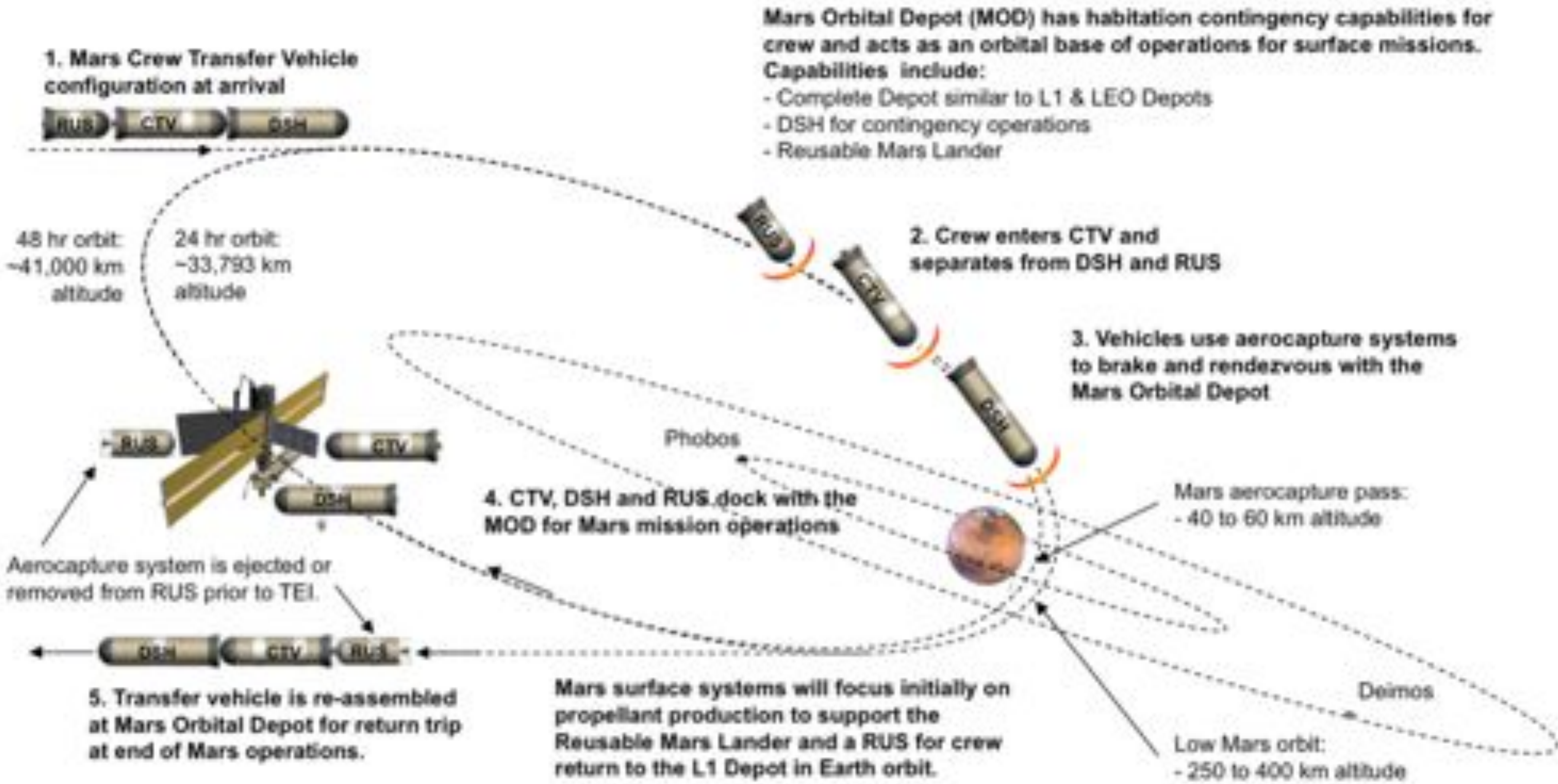


Figure 16. Mars Orbital Depot. *A typical crew mission going to the Mars Orbital Depot will consist of a RUS, CTV, and DSH. All three elements have an aerocapture capability and will separate and enter Mars orbit independently for rendezvous and docking with the depot. See Appendix A-7 Crew Mission Reference Profile to Mars orbit.*

Mars Semi-Cycler Mission Concept

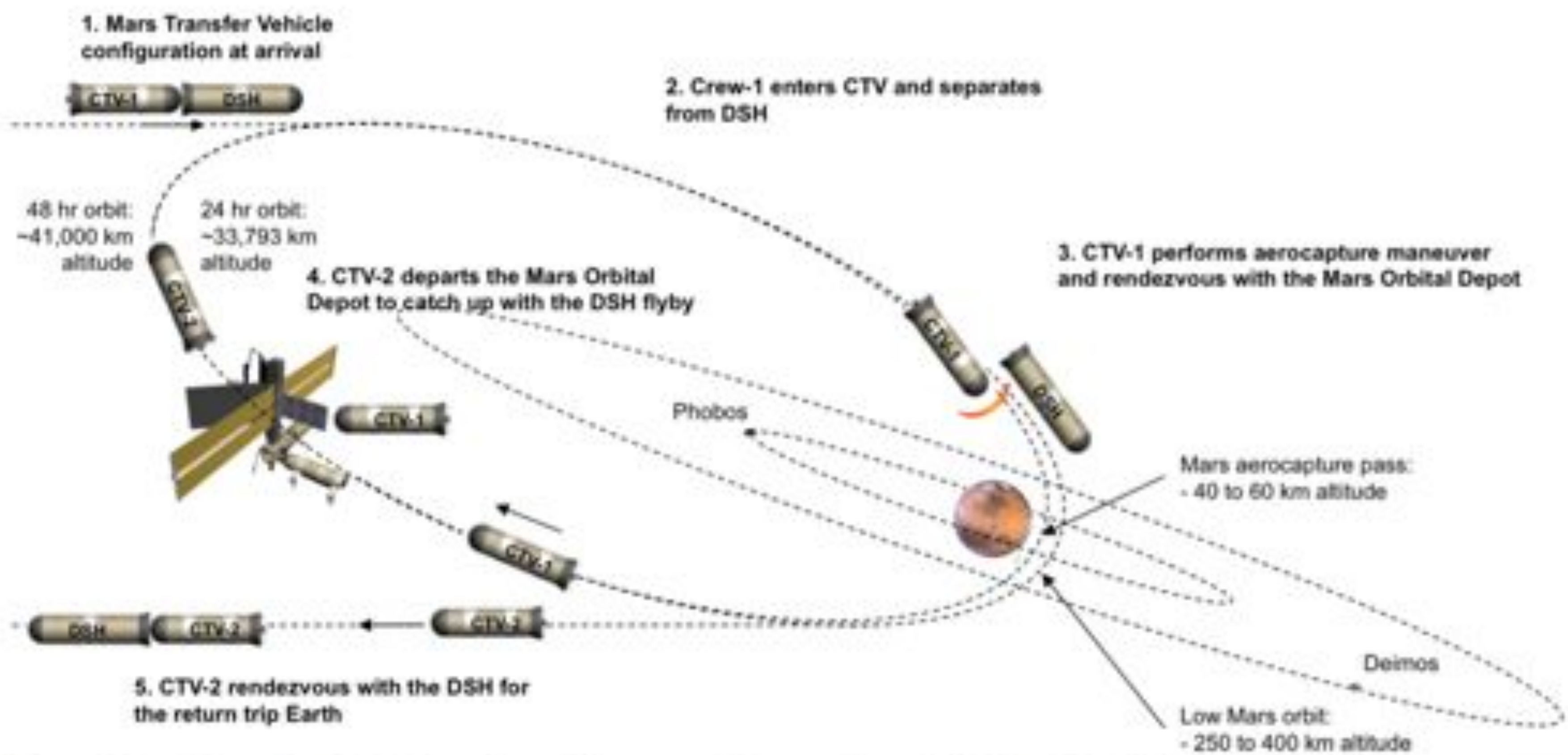
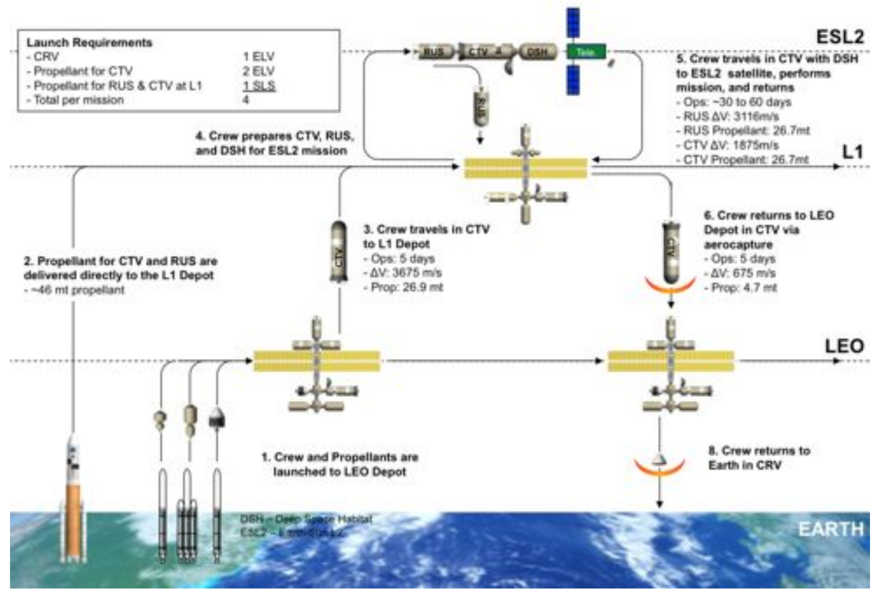
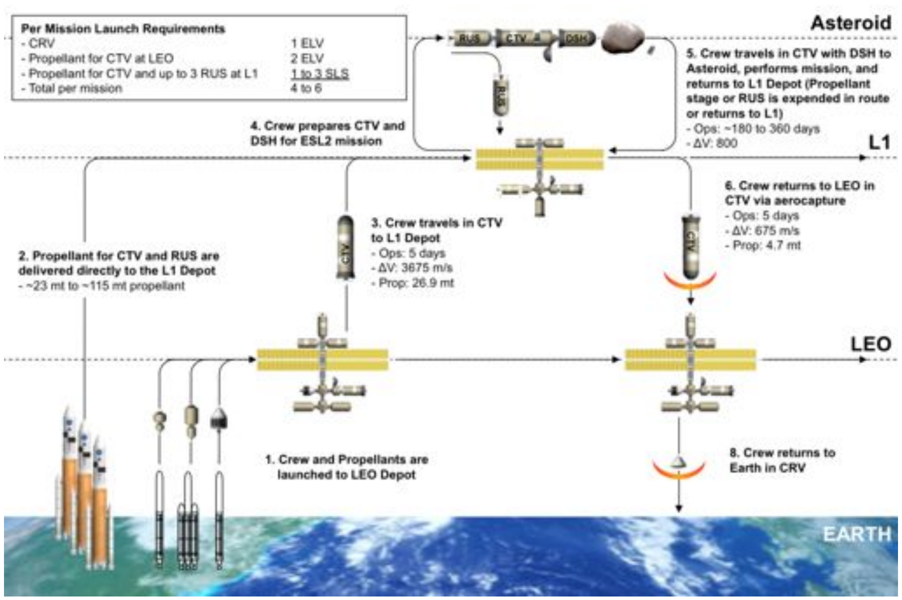


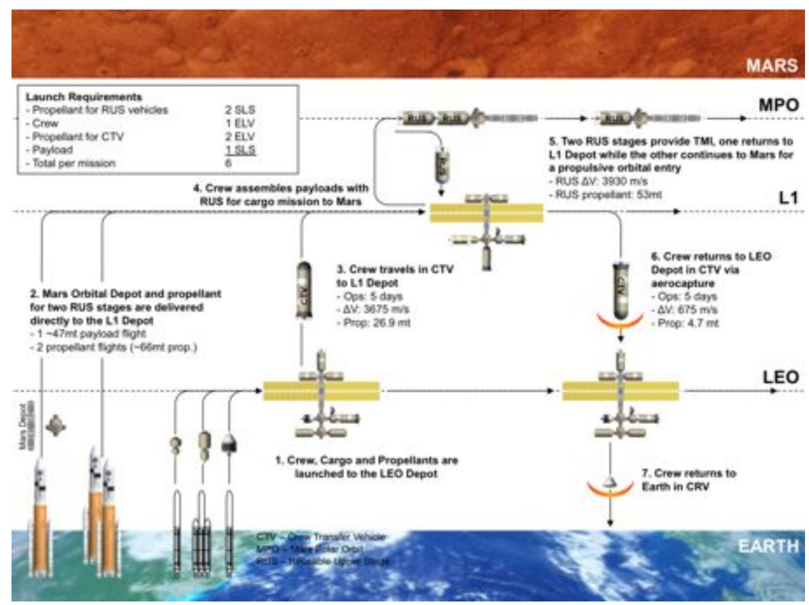
Figure 17. Mars Semi-Cycler. *A typical crew mission using a DSH in a Semi-Cycler orbit will have one crew transfer in their CTV to the Mars Orbital Depot while the other crew transfers in their CTV from the Mars Orbital Depot to the DSH as it passes by. Three RUS boosters, not shown, provide the initial TMI capability and the CTV provides the return TEI capability. See Appendix A-8 Semi-Cycler Crew Mission Reference Profile to Mars orbit.*

L1 Depot Missions
With SLS Integration

- **ESL2 Servicing Missions**
  - RUS, CTV, Small DSH
  - 4 Launches
- **Asteroid Missions**
  - 0 to 3 RUS, CTV, DSH
  - 4 to 6 Launches
- **Mars Cargo Missions**
  - 2 RUS, Payload
  - 6 Launches

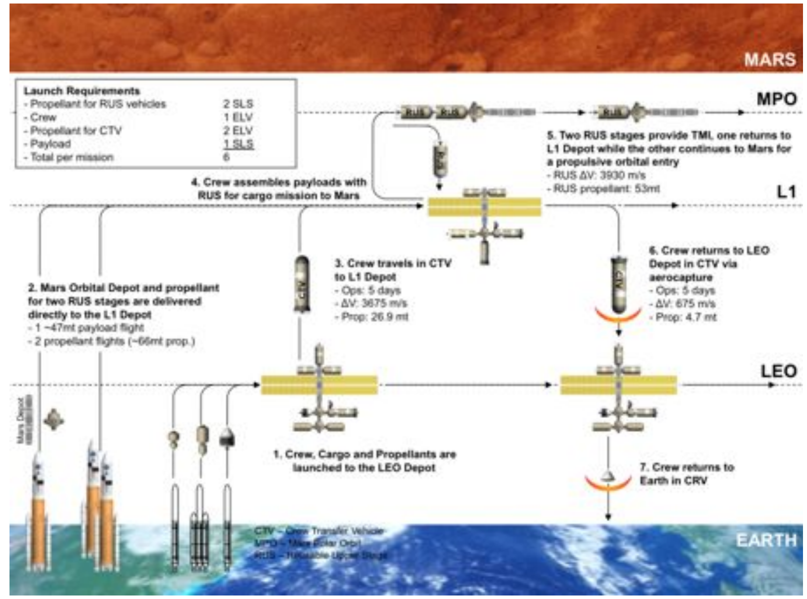


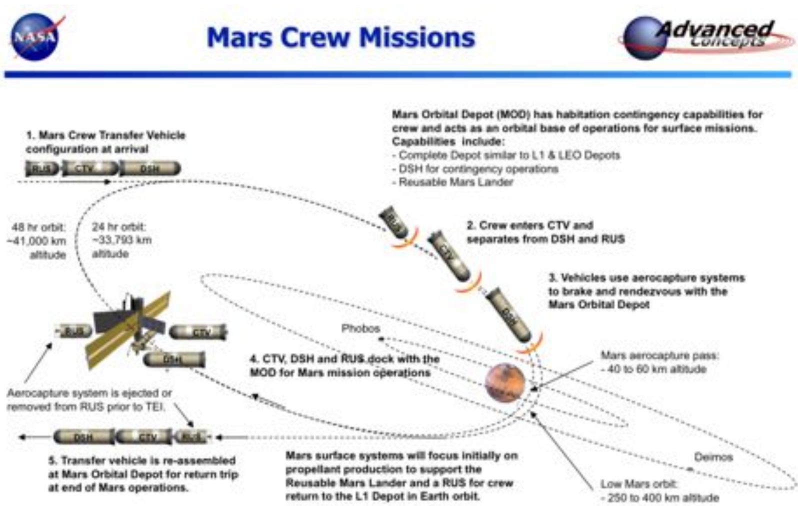


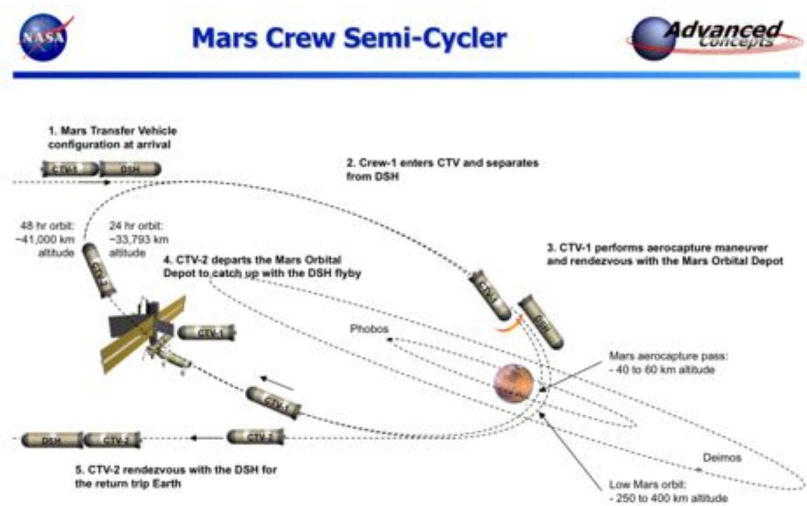


Mars Missions
With SLS Integration

- **Mars Orbital Depot Delivery**
  - 6 Launches
  - ~ 49 mt payload
- **Mars Crew Missions**
  - 6 to 7 Launches
- **Mars Crew Semi-Cycler Missions**
  - ~5 to 6 Launches (Preliminary)
  - ~4 to 5 Launches if TEI propellant comes from Mars Surface (Preliminary)







Conclusions

The propellant depot system described in this paper shows one way our current commercially available ELV infrastructure could provide for over 90% of the propulsion and propellants required to support simultaneously all of our commercial and exploration mission needs in the foreseeable future. The ability to place such a large percentage of the transportation mass into a competitive contracting environment should have tremendous economic impact by lowering space transportation cost for NASA and new commercial customers. The incremental development, high flight rates, reusability, and the multipurpose/multi-mission characteristics of this propellant depot infrastructure make it worthy of serious consideration as a part of a long-term development plan for human expansion into space. Establishment of a LEO Depot to support satellite servicing and future commercial and exploration missions, and then expanding quickly with the addition of a L1 Depot for exploration and development out to the Moon and then to Mars has great potential to permanently expand human presence beyond LEO.

The LEO Depot can support satellite servicing missions, new commercial enterprises, and human exploration missions beyond LEO through the L1 Depot. A typical GEO satellite servicing mission was found to require 4 Delta IV Heavy launches for crew and propellants utilizing a reusable CTV and RUS based at the LEO Depot. Both these vehicles have a propellant capacity of ~32 mt and are similar in design with the CTV having an added crew module and payload bay.

The L1 Depot supports all missions beyond the Earth-Moon L1 orbit including the Moon, ESL2, Asteroids, and Mars. The system utilizes the same CTV and RUS, and adds a Lunar Lander and a DSH. The Lunar Lander also utilized a ~32 mt propellant capacity and has many similarities to the size and design of the CTV and RUS. This type of commonality was a goal throughout the depot infrastructure development. A typical lunar mission was found to require 7 Delta IV Heavy launches, ESL2 missions required 9 launches, asteroid missions varied from 6 to 15 launches, and Mars missions varied from 14 to 21 launches once the depots and reusable in-space transportation elements were in place.

This reusable depot infrastructure should promote a robust market for existing commercial launch vehicles and new commercial services in space. Technology development by NASA focused on reusability and reliability in all the in-space systems for depots, transfer vehicles, Landers, and habitats has the potential to open up the space frontier to multiple human space operations conducted simultaneously within NASA and with commercial developers and international partners. NASA's development of reusable technologies for in-space systems will further stimulate the commercial market for development of the next generation of reusable launch vehicles. To accomplish this type of infrastructure NASA and the commercial sector may need to find new organizational structures because neither appears to have the resources or the mandate to do it alone. Continued analysis of this approach, defining organizational responsibilities for its development, and integrating complex cost modeling to analyze the many options, are the next steps needed to move forward with this propellant depot-based space transportation infrastructure.

Benefits

- **A Depot Infrastructure can utilize commercial crew and cargo services including:**
  - Propellant launch to the LEO Depot utilizing any commercial ELV with:
    - Potential for increased production of existing ELV systems
    - Potential for competitive bidding for propellant supply to the LEO Depot

- **Depot Infrastructures can be developed incrementally making it:**
  - Easier to fit within flat budgets
  - Avoiding simultaneous development of major hardware

- **Depot Infrastructures make it possible to develop vehicles that can be serviced on orbit which:**
  - Avoids production of new vehicles for every missions
  - Eliminates Lunar Lander "Grave Yards" on the surface of the Moon
  - Increases safety and reliability
  - Promotes reusable technologies applicable to future reusable launch vehicle development

- **Depot Infrastructures support multi-mission, multi-use capabilities including:**
  - Support to government and commercial missions simultaneously
  - Increasing the number of missions that can be done at the same time
  - Potential for increasing ground operations utilization and efficiency

Benefits

- **Depots can utilizes ISS heritage systems for servicing which:**
  - Makes use of proven technologies
  - Extends ISS standards into the next generation of space development
  - Utilizes ISS as part of the infrastructure (optional, in that ISS could become the LEO Depot)

- **Integrating SLS can provide heavy lift capability to Earth-Moon L1 Depot in fewer launches for many elements including:**
  - Payloads for all human missions to the Asteroids, Moon, and Mars
  - Propellants for missions to all destinations beyond GEO

- **Integrating SLS into a Depot Infrastructure can support reusable systems with less on orbit assembly:**
  - Depot delivery to Earth-Moon L1
  - Propellant delivery to the L1 Depot
  - Payload deliver to EML1 for Mars missions including payloads, propellant and propulsion stages

- **Integrating SLS into a Depot Infrastructure should lower launch cost through efficiency, increased production, competition, while providing significantly more lift capability than currently available**

Future Work

- **Exploring the benefits of Earth-Moon L2 over L1 as a servicing depot and outpost location**
  - L2 may have more benefits from a scientific perspective than L1
  - Orbital delta-V access to L1 and L2 is similar
- **Further development of the Mars surface exploration strategy utilizing the Mars Orbital Depot**
  - Could enables development of Mars surface propellant to support reusable landers
  - Could further decrease propellant requirements for return missions
- **Integrating current Orion / Multipurpose Crew Vehicle and Service Module into a future reusable transfer system with propellant depots**
  - Development of a Reusable Upper Stage could make the Orion/Service Module system reusable for transfers between ISS and an L1 Depot
  - RUS propellants would be required at both depots
  - Commercial crew and cargo services to ISS would be required
- **Further developing and demonstrating on-orbit cryogenic propellant storage and transfer is needed**

Backup / Appendix

GEO Satellite Servicing Missions

Event	Delta V	Isp	Mass Ratio	Propellant	Hardware	Mass Remaining
CTV + RUS				64741.5	19228	
Refuel				64741.5		83970
Boost Phase	1950	455	1.548	29728.8		54240.8
Separate Booster				2411.8	4300.0	47529.0
GTO Ins	556.00	455	1.133	9837.6		37691.5
GEO Ins	1783	455	1.491	12415.9		25275.6
Rend/Dock	25	310	1.008	308.7		24966.9
LEO Return Insertion	1783	455	1.491	8326.0		16640.9
Post-Aero	200	310	1.068	1589.7		15051.3
Rend/Dock	25	310	1.008	123.3		14928.0
Servicing Equipment					500	14428.0
Propulsion Stage					4300	10128.0
Nose Cap					1000	9128.0
TPS					2928	6200.0
Tail Flare					1000	5200.0
Crew Cabin w/ Crew of 3					5200.00	0.0
Main vehicle propellant				32601		
Booster Propellant				32141		
				2411.8		6711.8
Recover Booster to LEO	1950	455	1.548	2376.2		4336
Rend/Dock	25	310	1.008	35.5		4300.0
Booster Empty					4300	0.0

A-1. GEO Satellite Servicing Reference Profile. *See Figure 2 for a typical GEO satellite servicing mission using a Reusable Upper Stage and a Crew Transfer Vehicle. This profile uses one RUS as a booster for the CTV to reach GEO.*

Earth-Moon L1 Missions

Event	Delta V	Isp	Mass Ratio	Propellant	Hardware	Mass Remaining
CTV					16528	
Refuel				31255.9		47784
TLI	3200.00	455	2.049	24458.9		23325
L1 Insert (Lunar Enc)	450	455	1.106	2237.6		21087
Rend/Dock	25	310	1.008	191.0		20896
LEO Return Insertion	450	310	1.160	2901.4		17995
Post-Aero	200	310	1.068	1330.5		16664
Rend/Dock	25	310	1.008	136.5		16528
Payload					2000	14528
Propulsion Stage					4300	10228
Nose Cap					1000	9228
TPS					2928	6300
Tail Flare					1000	5300
Crew Cabin w/ Crew of 4					5300.00	0

A-2. CTV Reference Profile between LEO Depot and L1 Depot. *See Figures 6, 10, 13, 14, and 15 for a typical crew transfer in the CTV from the LEO Depot to the L1 Depot. This profile shows that the CTV was sized for regular transfers between the LEO Depot and the L1 Depot without additional booster requirements. The RUS was sized to match the CTV propellant capacity for standardization.*

Lunar Lander Missions

Event	Delta V	Isp	Mass Ratio	Propellant	Hardware	Mass Remaining
Lunar Lander					12102	
Refuel				31018.9		43121
TLI (from L1)	125.00	455	1.028	1191.2		41930
Lunar Orbit Insert (From L1)	650	455	1.157	5684.0		36246
ACS	5	310	1.002	68.9		36177
LS Braking Burn	1700	455	1.464	13284.1		22893
Final Desc & Landing	300	310	1.070	2356.8		20536
Drop Surface Payload					1154.16	19382
Liftoff	60	310	1.014	305.8		19076
Ascent to Lunar Orbit (L1)	2390	455	1.709	8037.6		11038
Rendezvous & Dock	25	310	1.008	90.4		10948
Crew & Effects					508	10440
Propulsion Stage					5953	4487
Crew Cabin					4487.00	0
Total Lander Propellant Used				31018.9		
Descent Propellant Used				22585.1		
Ascent Propellant Used				8433.8		
Cryo Impulse Propellant				28197		
LOX Impulse Prop. Capacity				24168.9		
LH2 Impulse Prop. Capacity				4028.1		
LOX Loaded at Launch		(FYI)	24652.2			
LH2 Loaded at Launch		(FYI)	4108.7			
Total LOX & LH2 Loaded at Launch			28760.9			
Storable Propellant Used/Loaded			2821.9		2878.36	

A-3. Lunar Lander Reference Profile. *See Figure 6 for a typical Lunar Lander mission from the L1 Depot to the surface of the Moon and back to the L1 Depot. The Lander is completely reusable with no separate ascent stage. The propellant capacity is the same as the CTV and RUS for standardization.*

L1 Cargo Missions

Event	Delta V	Isp	Mass Ratio	Propellant	Hardware	Mass Remaining
RUS Booster + RUS w/ Payload					48652	
Load Propellant				61466.9		110119
Undock & Standoff	20	315	1.006	710.7		109409
TLI-1	1380	455	1.362	29105.1		80303
Sep Booster					6352	73951
TLI-2	1820	455	1.504	24769.6		49182
MCC	25	315	1.008	396.4		48785
L1 Arrival	425	455	1.100	4432.3		44353
Rend/Dock	25	315	1.008	357.5		43995
Deliver Payload					33500	10495
Depart L1	425	455	1.100	953.5		9542
Retro LEO (Aerocapture)	200	315	1.067	598.2		8944
Return to LEO Base	50	315	1.016	143.6		8800
RUS Empty					8800	0
Booster Recovery						
				2052.3		6352
MCC	200	315	1.067	398.2		5954
Retro into LEO	1380	455	1.362	1583.9		4370
Rend/Dock LEO Base	50	315	1.016	70.2		4300
Booster Empty					4300	0
Booster Load				31868.1		
Mission Stage Load				31651.1		

A-4. RUS Cargo Reference Profile. *See Figures 9 and 14 for typical Reusable Upper Stage cargo transfer missions from the LEO Depot to the L1 Depot. This profile utilizes two RUS vehicles to deliver a 33.5 mt cargo from the LEO Depot to the L1 Depot. The second stage RUS has an aerocapture system for use on return to the LEO Depot. Many variations are possible to accommodate payload mass requirements.*

Earth-Sun L2 Missions

Event	Delta V	Isp	Mass Ratio	Propellant	Hardware	Mass Remaining
Lander/Ascent Empty w/payload					36028	
Load Propellant at L1				46015.4		82043
Depart L1	425.00	455	1.100	7453.9		74590
TL2I	166	455	1.038	2724.0		71866
ACS/MCC	50	315	1.016	1153.9		70712
ESL2 Arrival RUS Burn	575	455	1.138	8549.6		62162
Separate RUS				2633.2	4300	55229
ESL2 Arrival PS Burn	625	455	1.150	7218.6		48010
Drop ESL2 Payload					1000	47010
ESL2 Depart	1200	455	1.309	11085.4		35925
ACS/MCC	50	315	1.016	576.8		35348
Orbit correction	200	455	1.046	1549.4		33799
L1 Arrival	425	455	1.100	3070.7		30728
Habitat Module					16200	14528
Prop. Stage Crew Module					5300	9228
Nose Cap, TPS & Flare					4928	4300
Propulsion Stage					4300.00	0
RUS Propellant				22514		
Propulsion Stage (PS)Propellant				23501		
Sum				46015		
Difference				-986		
RUS Stage Return inert					4300	
Propellant				2633.2		6933.216543
Turnaround	1225	455	1.316	1664.5		5268.71
ACS/MCC*	250	315	1.084	539.0		4729.71
L1 Arrival	425	455	1.100	429.7		4300.00
RUS Stage					4300	0

A-5. ESL2 Mission Reference Profile using the RUS, CTV and DSH. *See Figure 10 for a typical crew transfer and return from the L1 Depot to service a telescope at the Earth-Sun L2 orbit. This profile uses a RUS, CTV, and a small DSH for the mission. The RUS booster delivers the CTV and DSH to ESL2 and returns to the L1 Depot. The CTV completes the mission and returns the DSH to the L1 Depot for resupply.*

Mars Orbital Depot Mission

Event	Delta V	Isp	Mass Ratio	Propellant	Hardware	Mass Remaining
Cargo Carrier with MOD + RUS Booster stages					62658	
Load Propellant				53816.2		116475
Undock & Standoff	20	315	1.006	751.7		115723
Depart L1	425	462	1.098	10361.8		105361
MCC	25	315	1.008	849.2		104512
TMI-1	800	462	1.193	16916.6		87595
Drop RUS	0				6306.4	81289
TMI-2	250	462	1.057	4364.0		76925
MCC	25	315	1.008	620.0		76305
Propulsive Capture	1300	462	1.332	19033.3		57271
Orbit Trim	50	315	1.016	919.5		56352
RUS (not re-used)					9300	47052
MOD	0				47051.959	0
		Boost Stage Propellant		30886	15443	per RUS
		Mission Stage Propellant		29936.9		
		Extra Propellant		5000		
		Total Propellant Load to L		65823		
Boost Stages Recovery						
				2006.4	4300	6306.4
Boost Stages Return	1000	462	1.247	1249.0		5057
MCC	50	315	1.016	81.2		4976
Periapsis Burn	200	462	1.045	214.9		4761
MCC	25	315	1.008	38.4		4723
L1 Arrival	425	462	1.098	422.9		4300
Boost Stages (RUS Cluster)					4300	0
	Boost Stage Propellant Load			31812		
	Transit Prop Used			3140.5		
	Transit Prop Sys as Delivered to L1			2520.4		

A-6. Mars Orbital Depot Delivery Reference Profile. *See Figure 14 for MOD delivery and typical cargo missions from Earth through the LEO and L1 Depots to Mars orbit. This profile uses two RUS boosters to deliver the MOD payload to Mars orbit. The first stage RUS booster returns to the L1 Depot. The second stage RUS booster does a propulsive capture at Mars to place the MOD payload into Mars orbit.*

Event	Delta V	Isp	Mass Ratio	Propellant	Hardware	Mass Remaining
CTV and DSH + RUS Boost stages					84887	
Load Propellant				146900		231787
Undock & Standoff	20	315	1.006	1496		230291
Depart L1	425	453	1.100	21011		209280
MCC	25	315	1.008	1687		207594
TMI-1	1350	453	1.355	54401		153192
Drop TMI Boost Stages					22243.7	130949
TMI-2 by CTV	650	453	1.158	17824		113124
MCC	25	315	1.008	912		112213
Sep CTV for Aerocapture					18696	93517
Drop TEI AeroShell					4500	89017
Post-Aero	200	315	1.067	5863		83154
Add CTV for Return Trip					17373	100527
Add TEI Stage					0	100527
Load TEI stage propellant				0		100527
TEI-1	1600	453	1.434	30403		70124
Drop TEI-1					4300	65824
TEI-2 (CTV)	500	453	1.119	7007		58817
MCC	50	453	1.011	785		58032
Separate CTV for Capture & L1 Arr					17373	40659
L1 Arrival	425	315	1.147	5226		35433
Rend/Dock with L1 Depot	25	315	1.008	286		35147
TEI Stages					0	35147
Deep Space Hab					33500	1647
TPS					5000	-3353
DSH Propulsion Stage					1147.2012	-4500
		Boost Propellant		87938	2.7480733	
		CTV Propellant		28527	0.8914668	
		TEI Propellant		30403	0.9501006	
		Total Propellant		156244	4.8826185	
		TMI Stages Recovery				
				9344	12900	22243.7
Boost Stages Return	1687.5	453	1.462	7030		15214
MCC	50	315	1.016	244		14969
Periapsis Burn	200	453	1.046	659		14310
MCC	25	315	1.008	115		14195
L1 Arrival	425	453	1.100	1295		12900
Boost Stages (3 RUS)					12900	0
		CTV Aerocapture to MOD				
				1323	17373	18695.88974
Post-Aero	200	315	1.067	1172		17524
Rend/Dock with MOD	25	315	1.008	151		17373
CTV					17373	
		CTV Aerocapture to L1				
				2373	15000	17373.10251
L1 Arrival	425	315	1.147	2233		
Rend/Dock with L1 Depot	25	315	1.008	140		
CTV					15000	

A-7. Crew Mission Reference Profile to Mars Orbit. *See Figure 15 for a typical Crew mission from the L1 Depot to the Mars Orbital Depot with return to the L1 Depot. This profile uses 3 RUS boosters to deliver a CTV, large DSH, and an RUS for the TEI maneuver for crew return. The TEI-RUS has an aerocapture system for Mars orbit entry that is then ejected prior to RUS use on return for the TEI maneuver.*

Semi-Cycler Missions

Semi-Cycler						
Event	**Delta V**	**Isp**	**Mass Ratio**	**Propellant**	**Hardware**	**Mass Remaining**
CTV + DSH Cycler + RUS Boost stages					105674	
Load Propellant				90191.9		195866
Undock & Standoff	20	315	1.006	1264.0		194602
Depart L1	425	462	1.098	17424.6		177177
MCC	25	315	1.008	1428.1		175749
TMI-1	1700	462	1.455	54985.3		120764
Separate TMI Stage(s)					24252	96512
TMI-2 (CTV#1)	250	453	1.058	5281.3		91231
					0	91231
MCC	25	315	1.008	973.4		90258
Separate CTV#1					40983	49275
Pick Up CTV#2					22278	71553
Transfer Propellant to CTV#2				0		71553
MCC	25	315	1.008	397.2		71156
Separate CTV#2					22278	48877
Post-Aero	200	315	1.067	4460.9		44416
L1 Arr	425	462	1.098	3977.0		40439
Aerobrake for Hab					5000	35439
Deep Space Hab					33500	1939
Storable Propulsion Module					1939	0
Needs to separate the TMI stage and account for return prop & transfer tanks						
					2.70	21613.3987
		Boost Stage Propellant		86454		
		Spacecraft Propellant		8835		
		Transferrable propellant		0		
		CTV#1 Propellant		31264.5		
		CTV#2 Propellant		23548.8		
Boost Stages Recovery						
				11351.5	12900	24251.5
TMI stage(s) Return	2125	462	1.598	9079.5		15172
MCC	50	315	1.016	243.6		14928
Periapsis Burn	200	462	1.045	644.7		14284
MCC	25	315	1.008	115.1		14169
L1 Arrival	425	462	1.098	1268.7		12900
Boost Stages (3 RUS, no aero)					12900	0

CTV Stop & Go						
Event	**Delta V**	**Isp**	**Mass Ratio**	**Propellant**	**Hardware**	**Mass Remaining**
CTV-1 Empty with Payload					15000	
TEI Propellant				23550		
Propellant on board				2433		40983
Aerocapture pass						
Post-Aero	200	453	1.046	1804.2		39179
MCC	25	315	1.008	315.8		38863
Rend & Dock MOD	25	315	1.008	313.3		38550
Top off Propellant from MOD supply				0.0		38550
Separate from MOD	25	315	1.008	310.7		38239
TEI	2350	453	1.697	15708.7		22531
MCC	50	453	1.011	252.2		22278
(CTV 2 Joins DSH near Mars)						
(CTV 2 Separates from DSH near Earth)						
Earth Arrival Braking	1060	453	1.269	4729.2		17549
Post-Aero	200	453	1.046	772.6		16777
MCC	25	315	1.008	135.2		16641
L1 Arr	425	453	1.100	1518.3		15123
Rend & Dock	25	315	1.008	121.9		15001
CTV					15000	1
CTV-2 Propellant				23548.8		

A-8. Semi-Cycler Crew Mission Reference Profile to Mars Orbit. *See Figure 16 for a typical Crew Semi-Cycler mission concept from the L1 Depot to the MOD and return to the L1 Depot. This profile uses three RUS boosters to deliver a CTV and large DSH on a Mars fly-by trajectory. The CTV-1 is swapped with CTV-2 during the fly-by. The aerocapture system on the DSH is utilized on return to the L1 Depot for aero braking into Earth orbit.*

Nomenclature

ACS	=	Attitude Control System
Aero	=	Aerocapture
Arr	=	Arrival
B	=	Billion
CRV	=	Crew Return Vehicle
Cryo	=	Cryogenic
CTV	=	Crew Transfer Vehicle
Delta-V	=	Δv, Change in velocity
Desc	=	Descent
DSH	=	Deep Space Habitat
ELV	=	Expendable Launch Vehicle
EML1	=	Earth-Moon Lagrange point 1
ESL2	=	Earth-Sun Lagrange point 2
EVA	=	Extra-Vehicular Activity
GEO	=	Geosynchronous orbit
hr	=	hour
Isp	=	I_{sp}, Specific impulse
ISS	=	International Space Station
kg	=	kilograms
km	=	kilometers
km/s	=	kilometers per second
L1	=	Earth-Moon Lagrange point 1
LEO	=	Low-Earth-Orbit
LH2	=	Liquid Hydrogen
LLO	=	Low-Lunar-Orbit
LOX	=	Liquid Oxygen
LS	=	Lunar Surface
M	=	Million
MAWS	=	Manned Autonomous Work Station, Human Free-Flyer, FlexCraft
m	=	meters
m/s	=	meters per second
MCC	=	Mid Course Correction
MLO	=	Mars Low Orbit
MOD	=	Mars Orbital Depot
MPO	=	Mars Polar Orbit
mt	=	metric tons
NASA	=	National Aeronautics and Space Administration
Ops	=	Operations
Prop.	=	Propellant, propellant stage or upper stage
PS	=	Propulsion Stage
Rend	=	Rendezvous
Retro	=	Retroactive or reverse thrust
RUS	=	Reusable Upper Stage
Sat	=	Satellite
Sep	=	Separate
SEP	=	Solar Electric Propulsion
TDRSS	=	Tracking and Data Relay Satellite System
TEI	=	Trans-Earth Injection
Tele.	=	Telescope
TLI	=	Trans-Lunar Injection
TL2I	=	Trans-ESL2 Injection
TMI	=	Trans-Mars Injection
TPS	=	Thermal Protection System
US	=	United States

Credits

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